Neutrino Experiment Xenon TPC – the present, and what's ***NEXT***…

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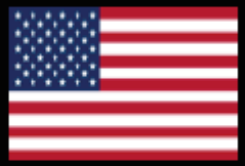
NEXT Collaboration

~~CIEMAT~~ (Madrid) • U. Girona • ~~IFAE (Barcelona)~~ •
IFIC (Valencia) • U. Santiago • U.P.Valencia • U. Zaragoza



LBNL • Texas A&M • UTA • ISU

U.Aveiro • U. Coimbra

CEA (Saclay)

JINR (Dubna)

UAN (Bogota)

Spain provides:

Most of the collaborators

Most secured funding

Host Laboratory - LSC

Key contributions from international groups

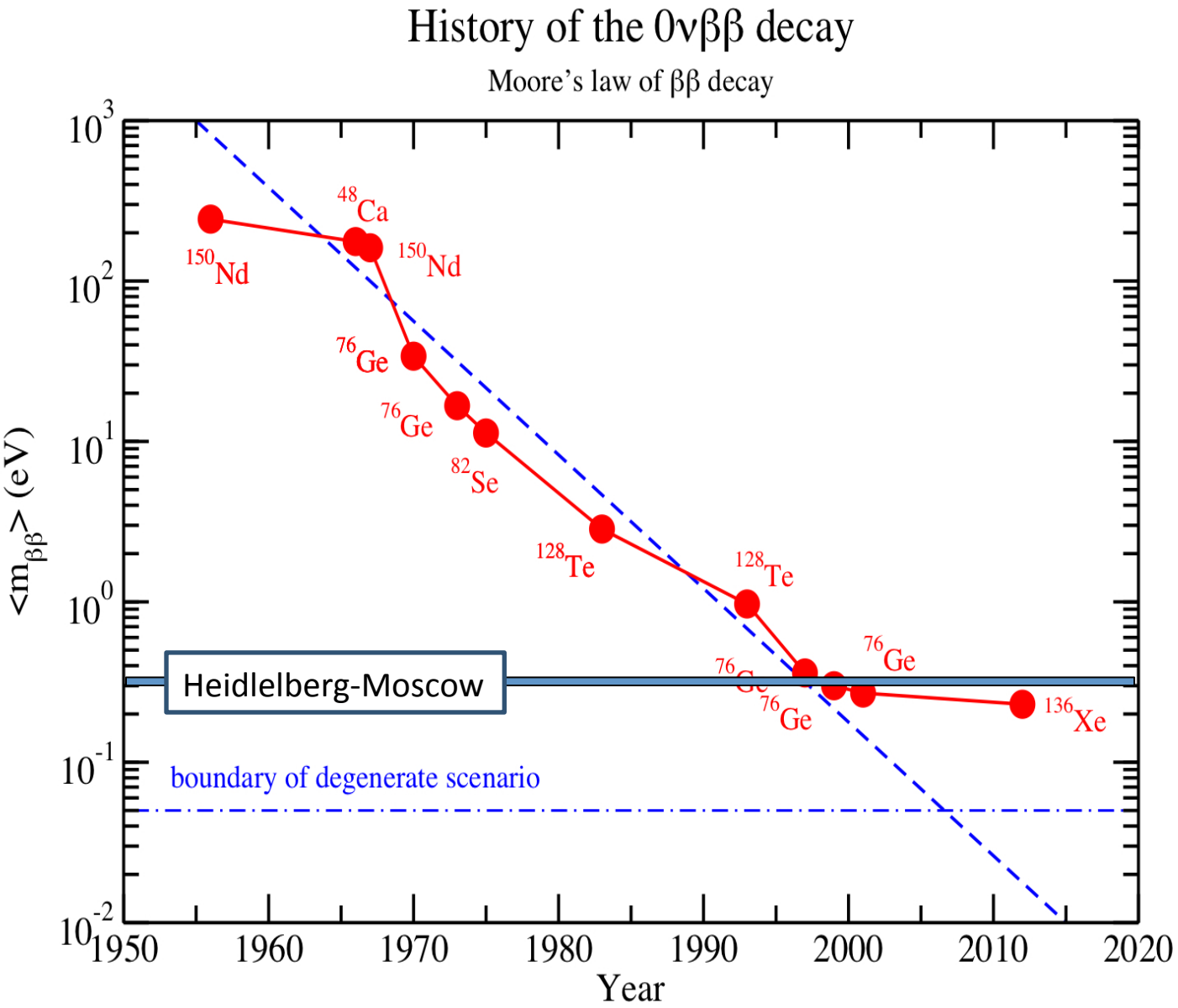
Engineering and integration

TPC expertise

high-pressure gas detectors

Xenon supply & enrichment

ββ trends (updated Elliott/Vogel plot by Vogel)



Historically, there are > 100 experimental limits on $T_{1/2}$ of the 0νββ decay.
Here are the records expressed as limits on $\langle m_{\beta\beta} \rangle$ using one set of nuclear matrix elements (RQRPA of Simkovic et al. 2009.)

During the last decade the complexity and cost of experiments has increased very dramatically. The slope constant is now leveling off!

Perspective

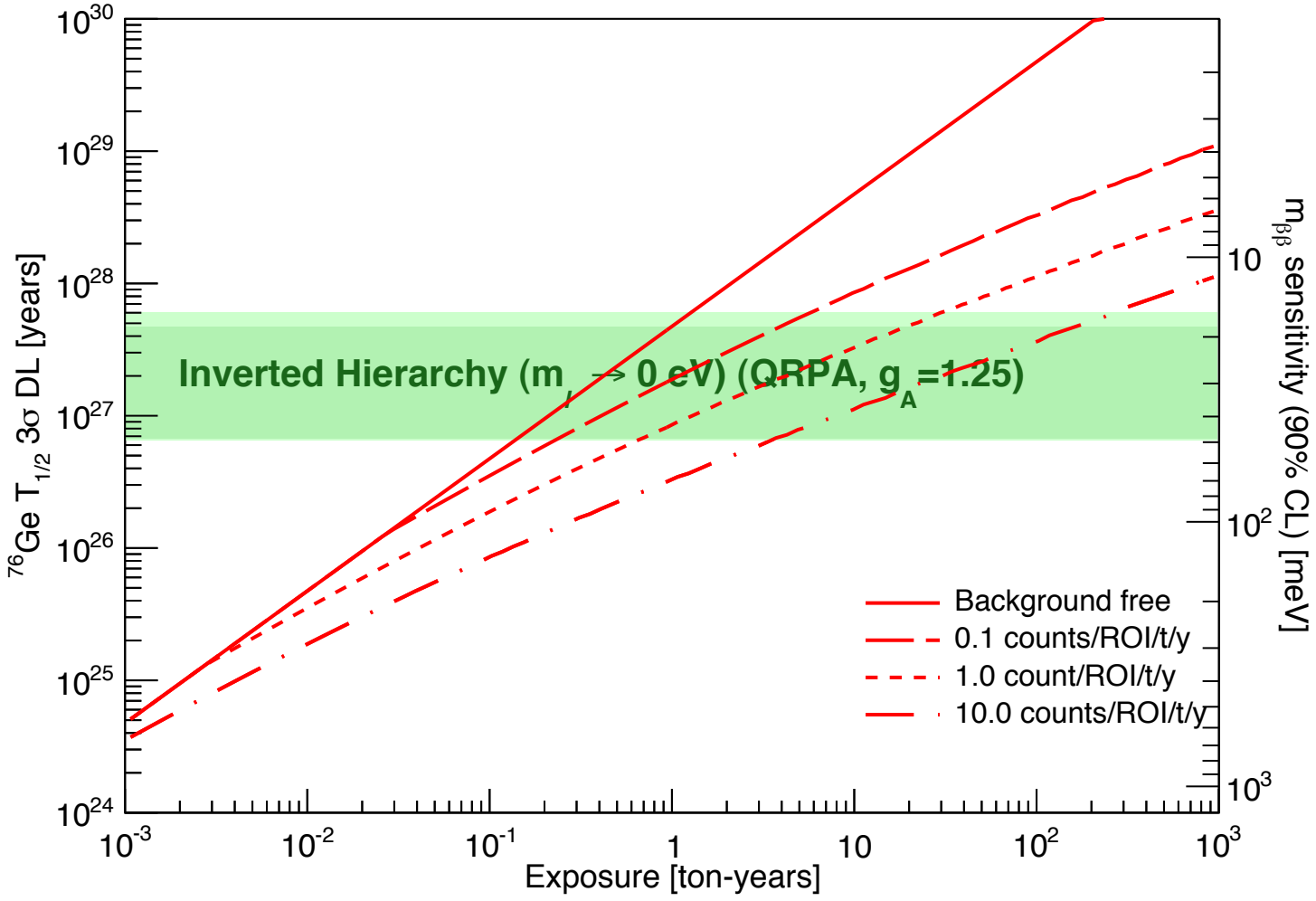
- NLDBD has entered a new era:

  "Maybe not big/good enough to succeed,

  but too expensive to fail"

- Failure: *background-limited result*
- Energy resolution, shielding, radio-purity,… not (yet) sufficient to reject all backgrounds
- A **discovery class** experiment should aim for zero background well into inverted domain

Sensitivity, Background and Exposure



Various Levels of Confidence in a Result

- Preponderance of the evidence:
  - Correct peak energy with no 2-ν contamination
  - Single-site energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
- Beyond a reasonable doubt:
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the excited state decay
  - See the process consistently in several isotopes
- Smoking Guns:
  - Observe the daughter atom
  - A background-free positive result with enriched isotope – AND:
  - See no peak with depleted isotope – no other changes to detector

Why Xenon Gas?

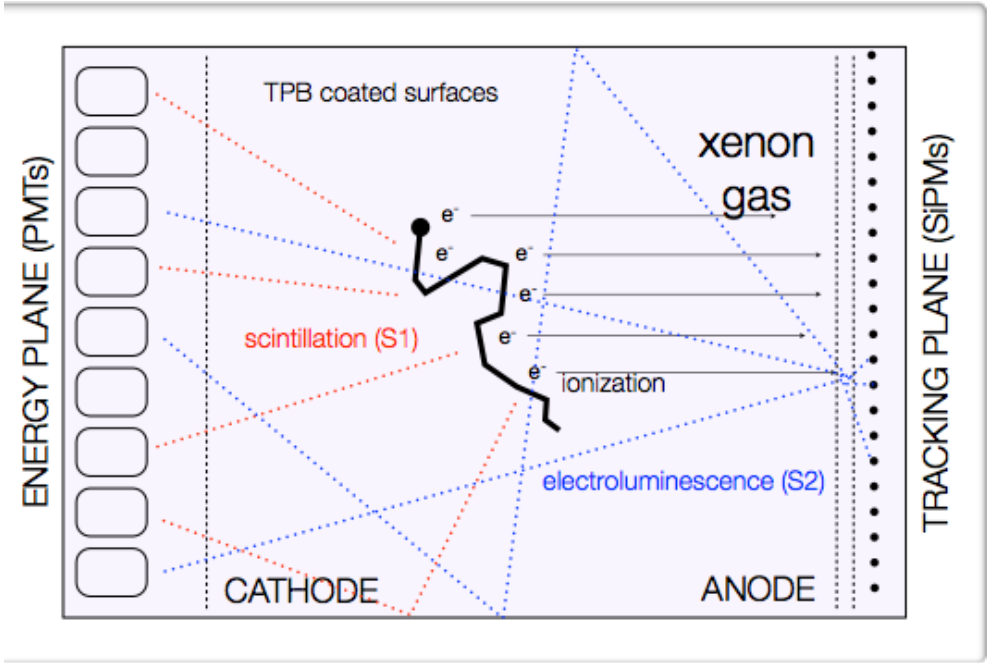
- **Excellent intrinsic energy resolution:**
  $\delta E/E < 3 \times 10^{-3}$ FWHM at ^{136}Xe $Q_{\beta\beta}$ (2457 KeV)
  This will be hard to approach in real-life, but maybe 5×10^{-3} FWHM

- **Topology available for background rejection**
  Single electrons (γ-rays) create one endpoint blob
  Double-beta decay events create two endpoint blobs

- **Gas phase allows molecular admixtures**
  Reduced diffusion for better tracking, event integrity, MS measurement, possible wavelength-shifting, Penning effect, …

- **New idea for daughter identification…**
  Barium tagging at high pressure…! ??

NEXT: A light TPC



EL mode is essential to get lineal gain, therefore avoiding avalanche fluctuations and fully exploiting the excellent Fano factor in gas

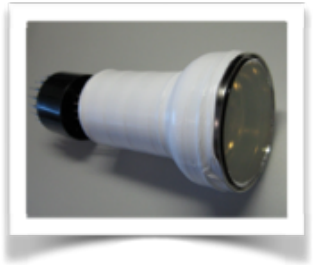
- It is a High Pressure Xenon (HPXe) TPC operating in EL mode.
- It is filled with 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane), which also provide t0.
- The event topology is reconstructed by a plane of radiopure silicon pixels (MPPCs) (tracking plane).

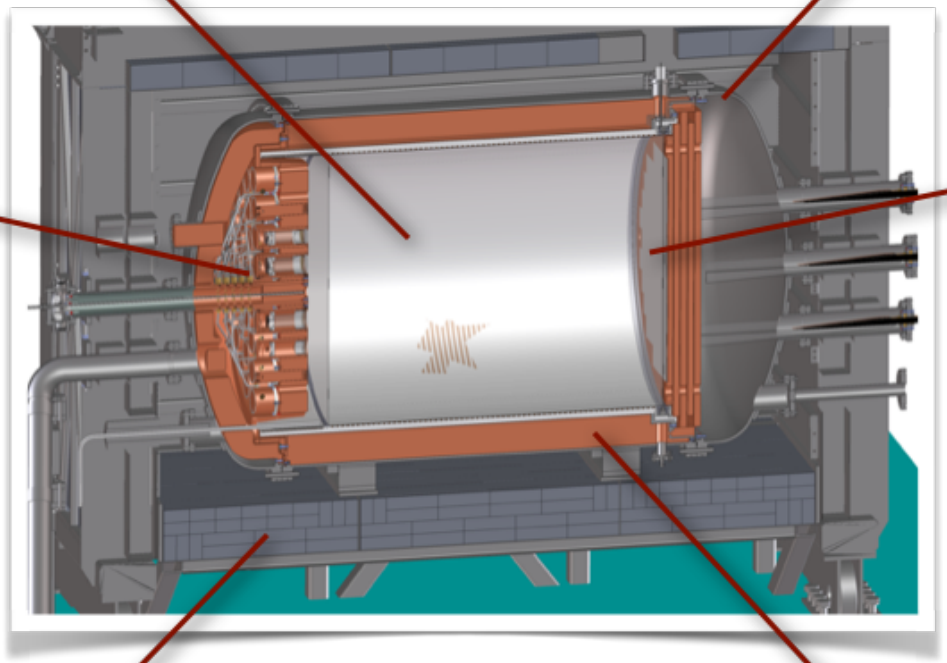
NEXT 100 kg detector at LSC: main features

Time Projection Chamber:
100 kg active region, 130 cm drift length

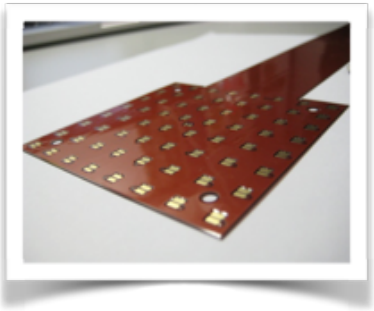
Pressure vessel:
stainless steel,15 bar max pressure

Energy plane:
60 PMTs,
30% coverage





Tracking plane:
7,000 SiPMs,
1 cm pitch

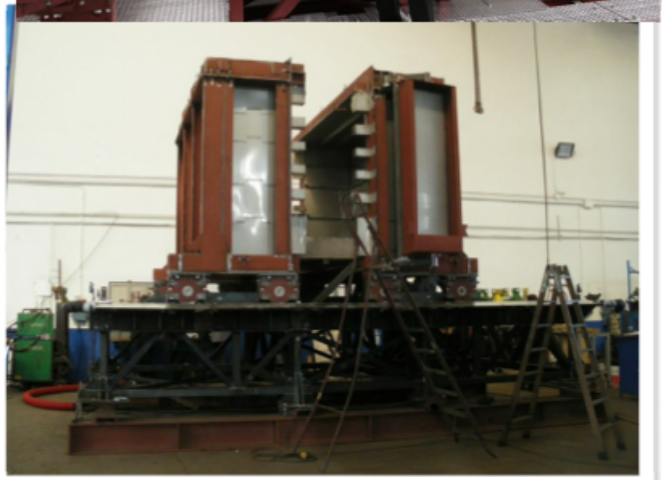


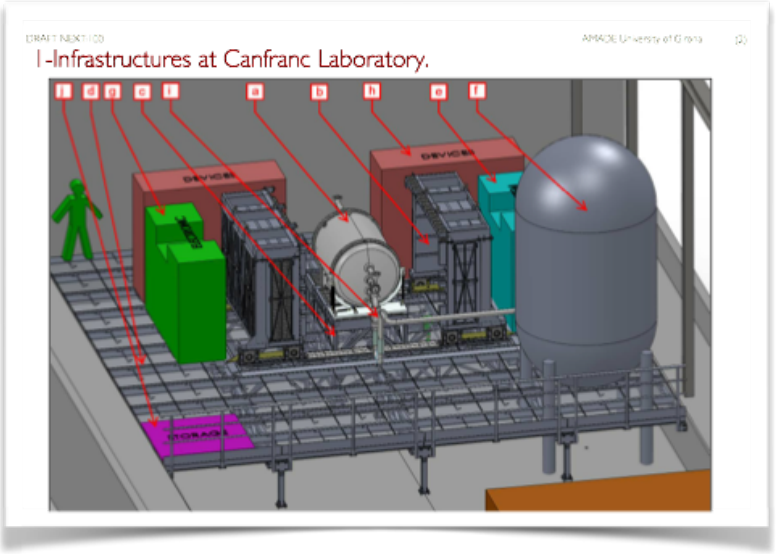
Outer shield:
lead, 20 cm thick

Inner shield:
copper, 12 cm thick

NEXT-100 Pressure Vessel

NEXT at LSC





Infrastructures: platform, lead castle, gas system, emergency recovery system, completed. First phase of experiment starts in 2015. In stock, 100 kg of enriched xenon and 100 kg of depleted xenon.

NEXT Platform and Pb Castle at LSC

65 t of Pb sheets from OPERA disassembled bricks received as a loan (for all the duration of NEXT) by INFN

Pb bricks (mainly of standard form) produced by Tecnibusa (5% loss)

Three deliveries
- **7 July**
- **11 August**
- **29 September**

Cleaning and assembly made by NEXT

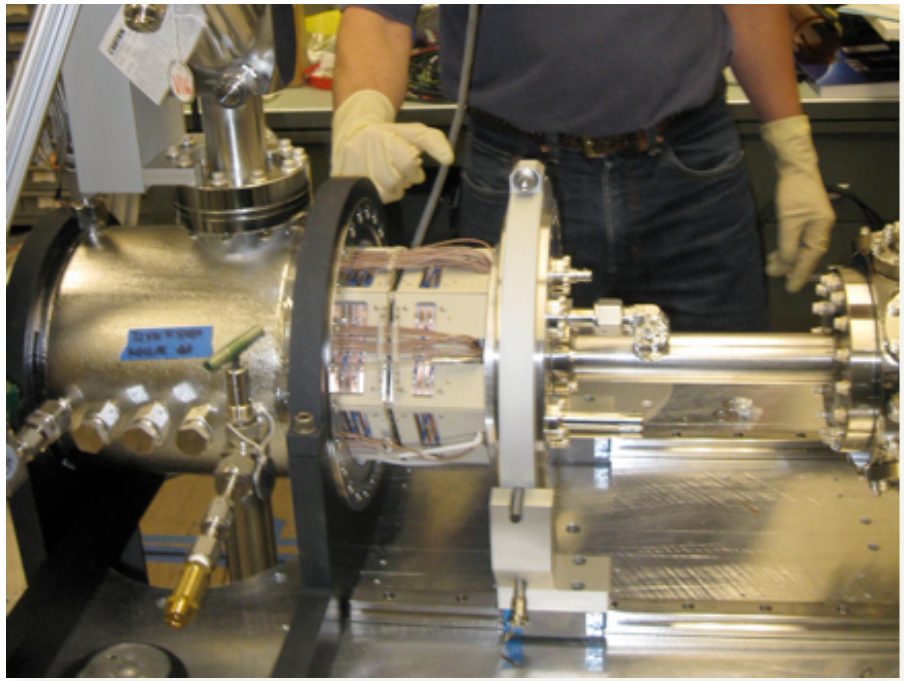
NEXT Expected Performance

Systematic assay of ALL detector components at the LSC HPGe facility
Development of full MonteCarlo simulations

Selection criterion	$\beta\beta0\nu$	$\beta\beta2\nu$	^{208}Tl	^{214}Bi
Fiducial, single track $E \in [2.4, 2.5]$ MeV	0.4759	8.06×10^{-9}	2.83×10^{-5}	1.04×10^{-5}
Track with 2 blobs	0.6851	0.6851	0.1141	0.105
Energy ROI	0.8661	3.89×10^{-5}	0.150	0.457
Total	0.2824	2.15×10^{-13}	4.9×10^{-7}	4.9×10^{-7}

Detector subsystem	^{208}Tl	^{214}Bi	*Total*
Pressure vessel	< 0.23	< 0.06	< 0.29
Energy plane	< 0.57	< 2.10	< 2.67
Tracking plane	< 0.40	< 0.50	< 0.90
Electric-field cage	< 0.15	< 0.81	< 0.96
Inner shielding	< 0.05	< 0.7	< 0.75
Outer shielding	0.027(13)	0.25(14)	0.28(14)
Total	< 1.43	< 4.42	< 5.85 10^{-4} /(keV kg yr)

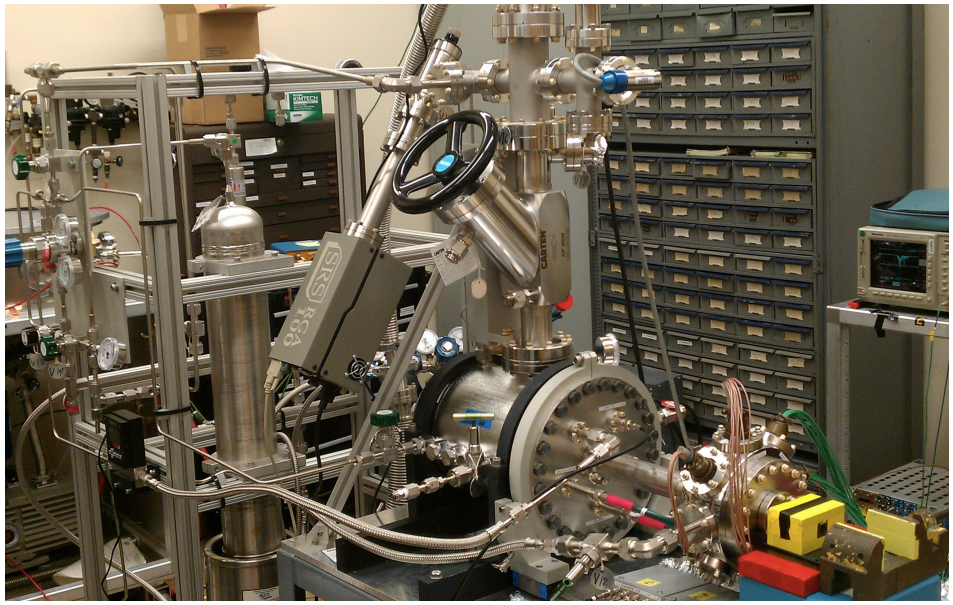
EL Prototypes

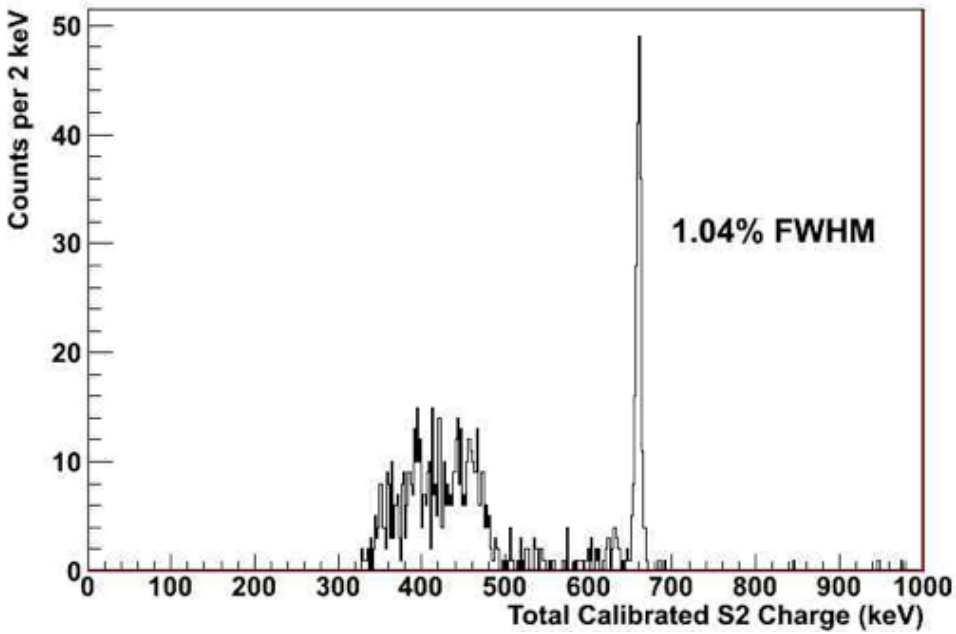


NEXT-DBDM
LBNL-Berkeley

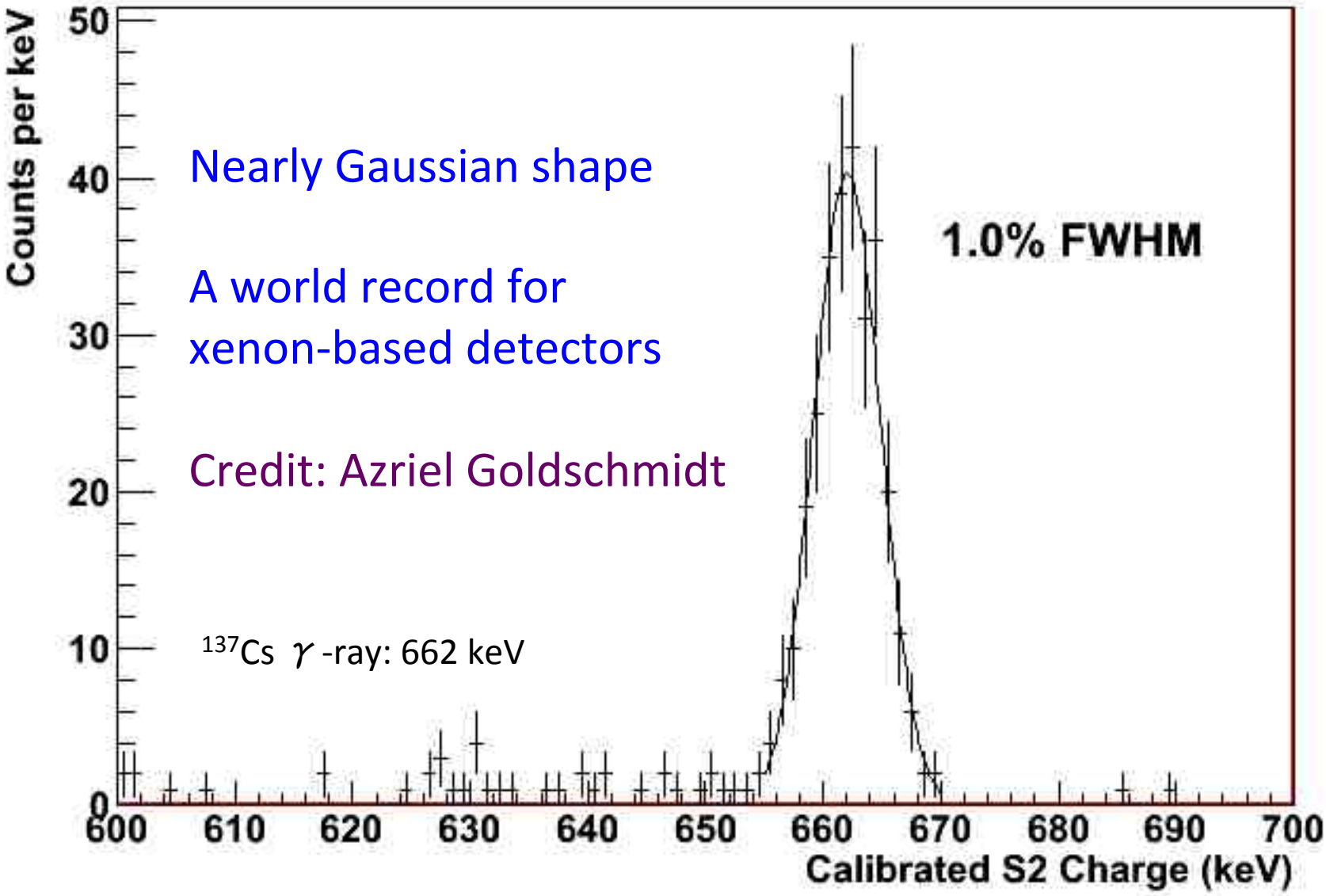
NEXT-DEMO
IFIC-Valencia

NEXT-DBDM. Energy resolution

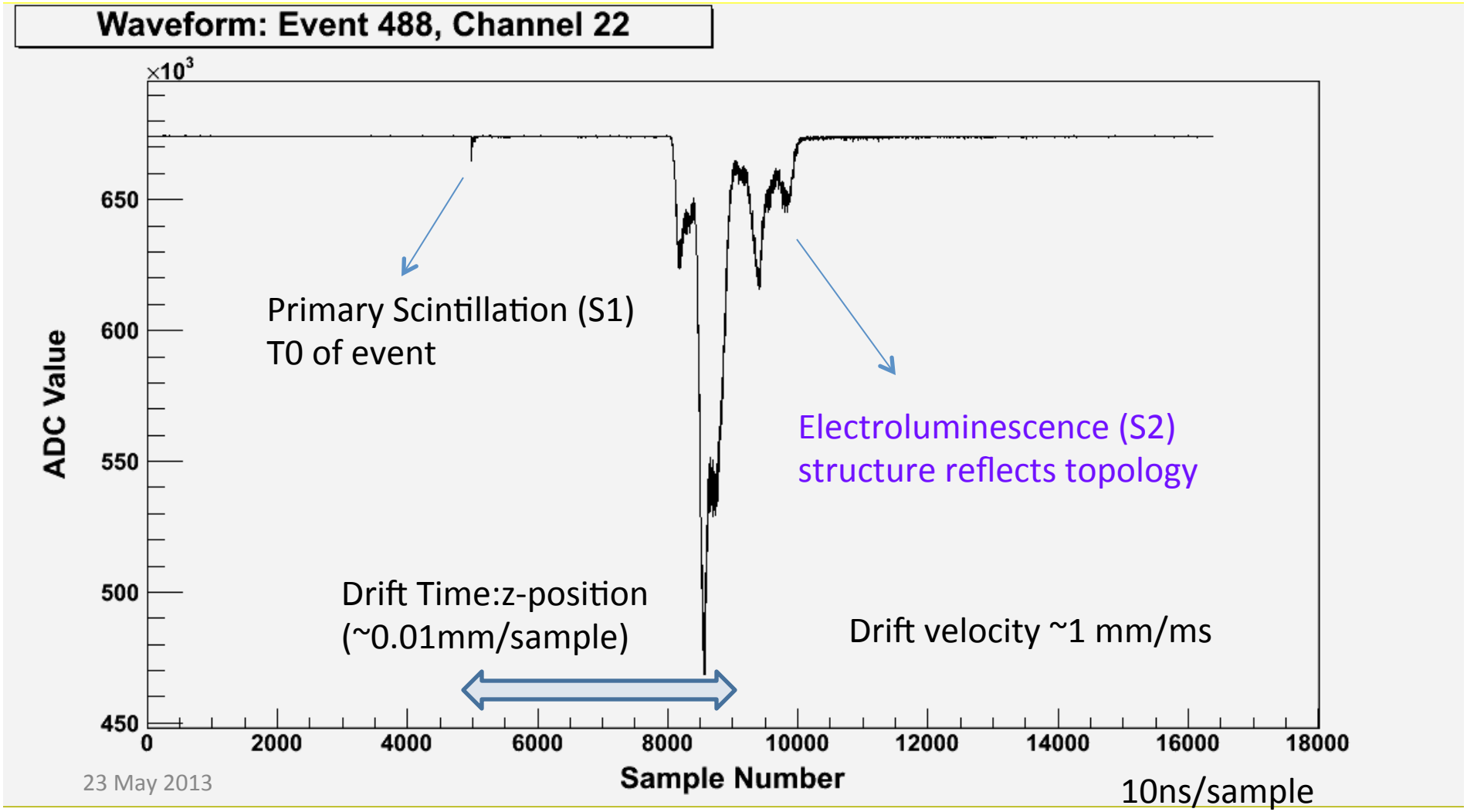




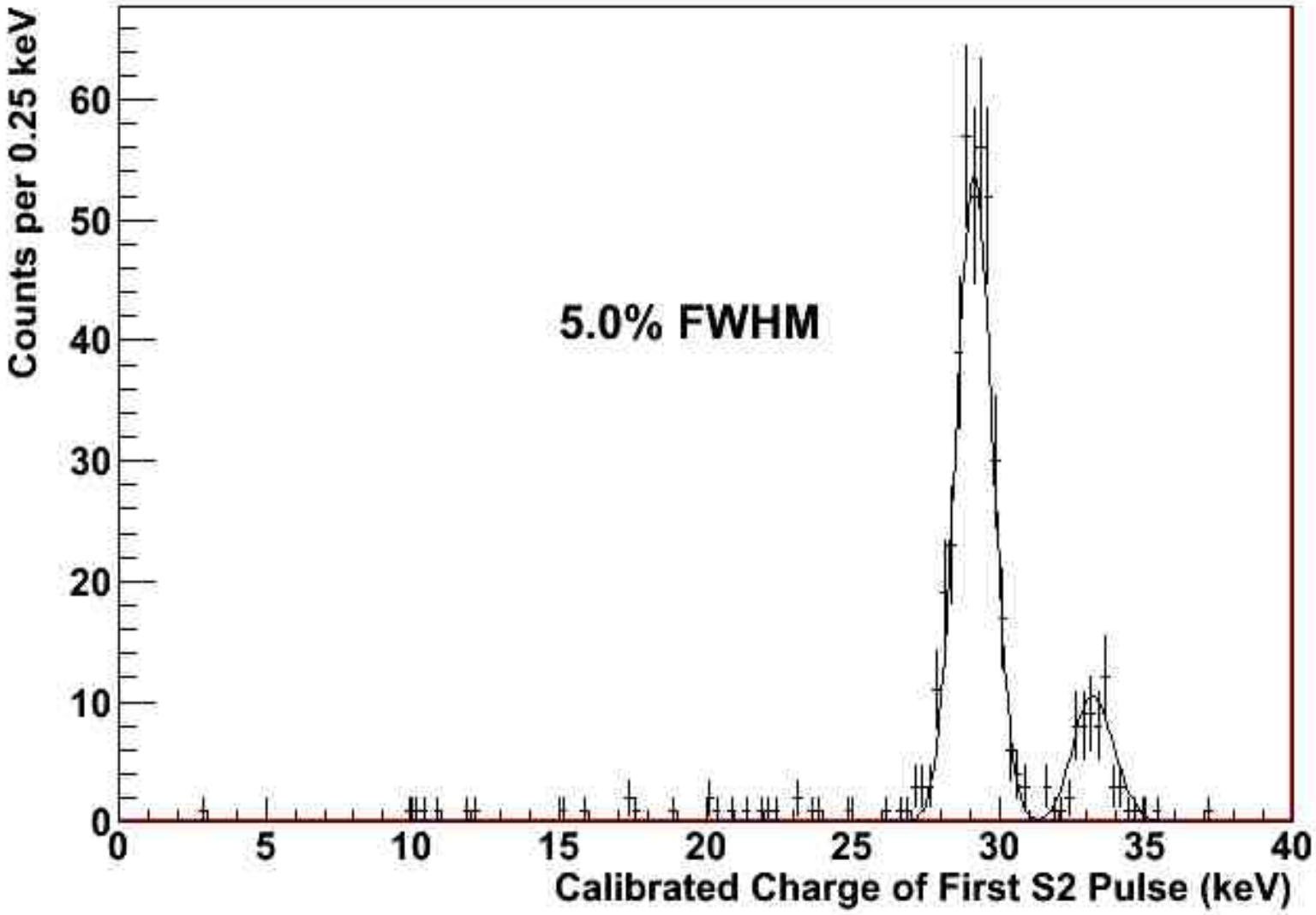
NEXT-DBDM obtains an extraordinary energy resolution: 1.04% at Cs-137 peak (about 0.53% @ Qbb)
No tracking yet. Impose hard fiducial cut which in practice selects only events in the center of the chamber.


Counts per keV
50
40
30
20
10
0
600
610
620
630
640
650
660
670
680
690
700
Calibrated S2 Charge (keV)
Nearly Gaussian shape
A world record for
xenon-based detectors
Credit: Azriel Goldschmidt
1.0% FWHM
^{137}Cs γ -ray: 662 keV

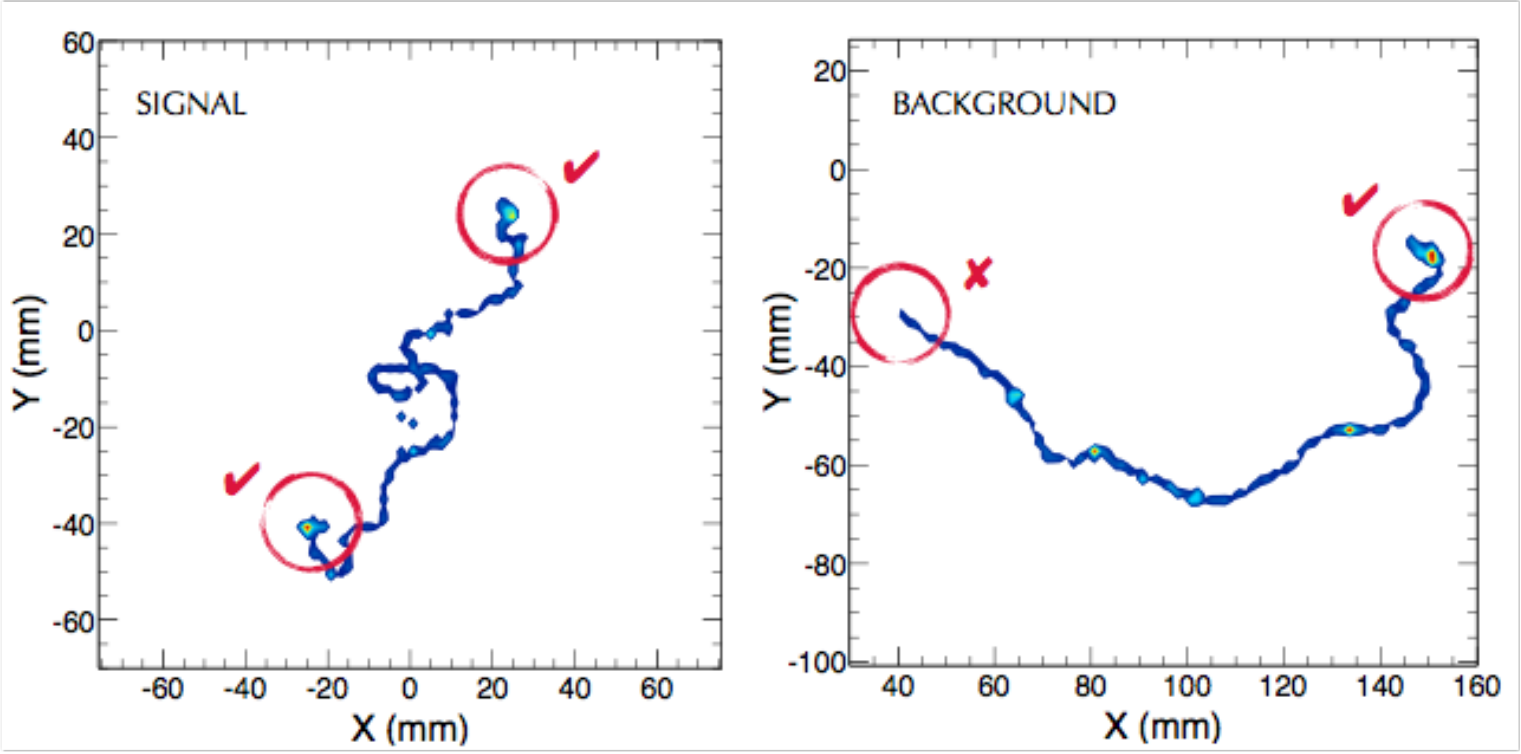
A typical ^{137}Cs γ waveform (sum of 19 PMTs)
~300,000 detected photoelectrons



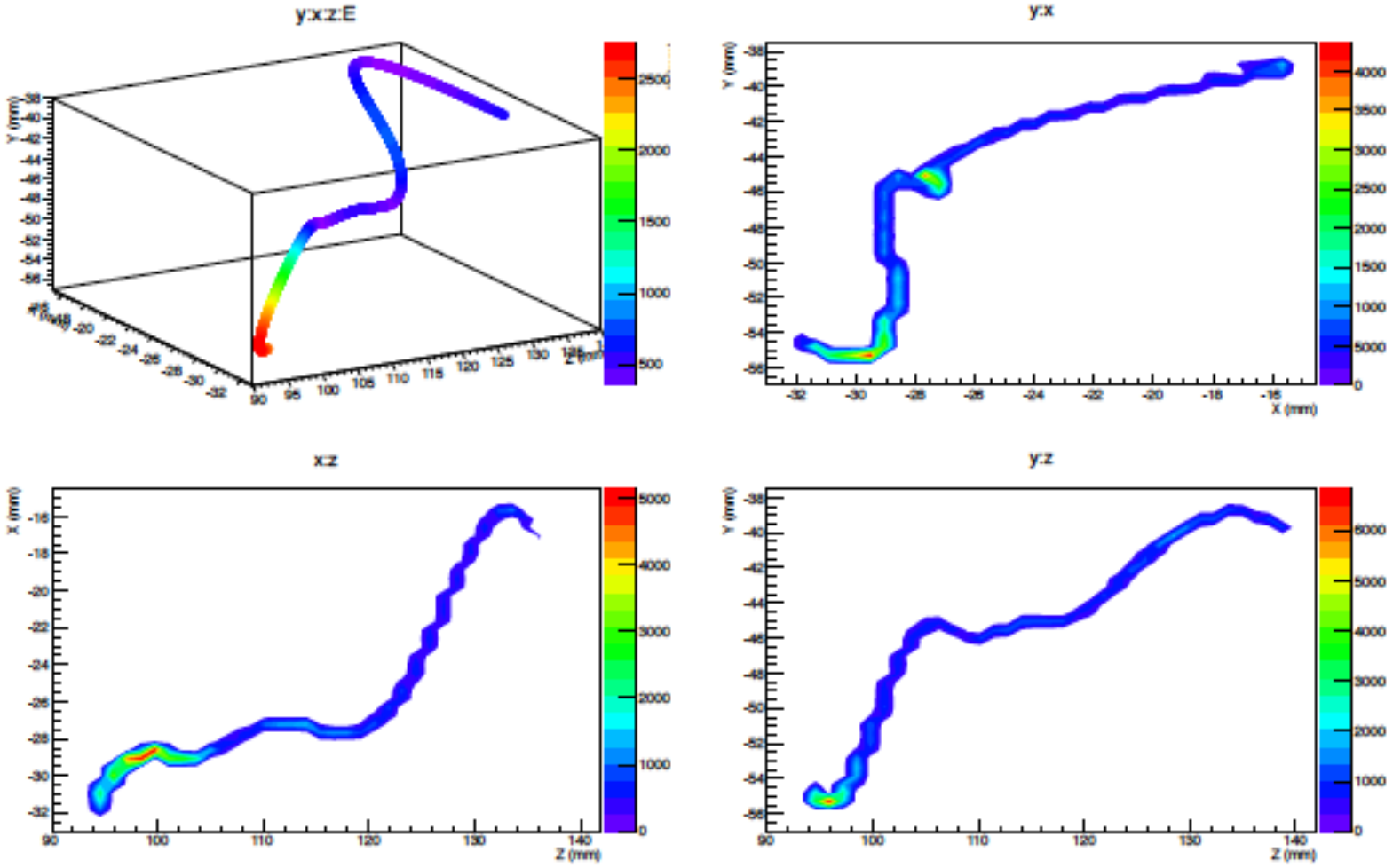
The x-ray peaks at ~30 keV are captured precisely



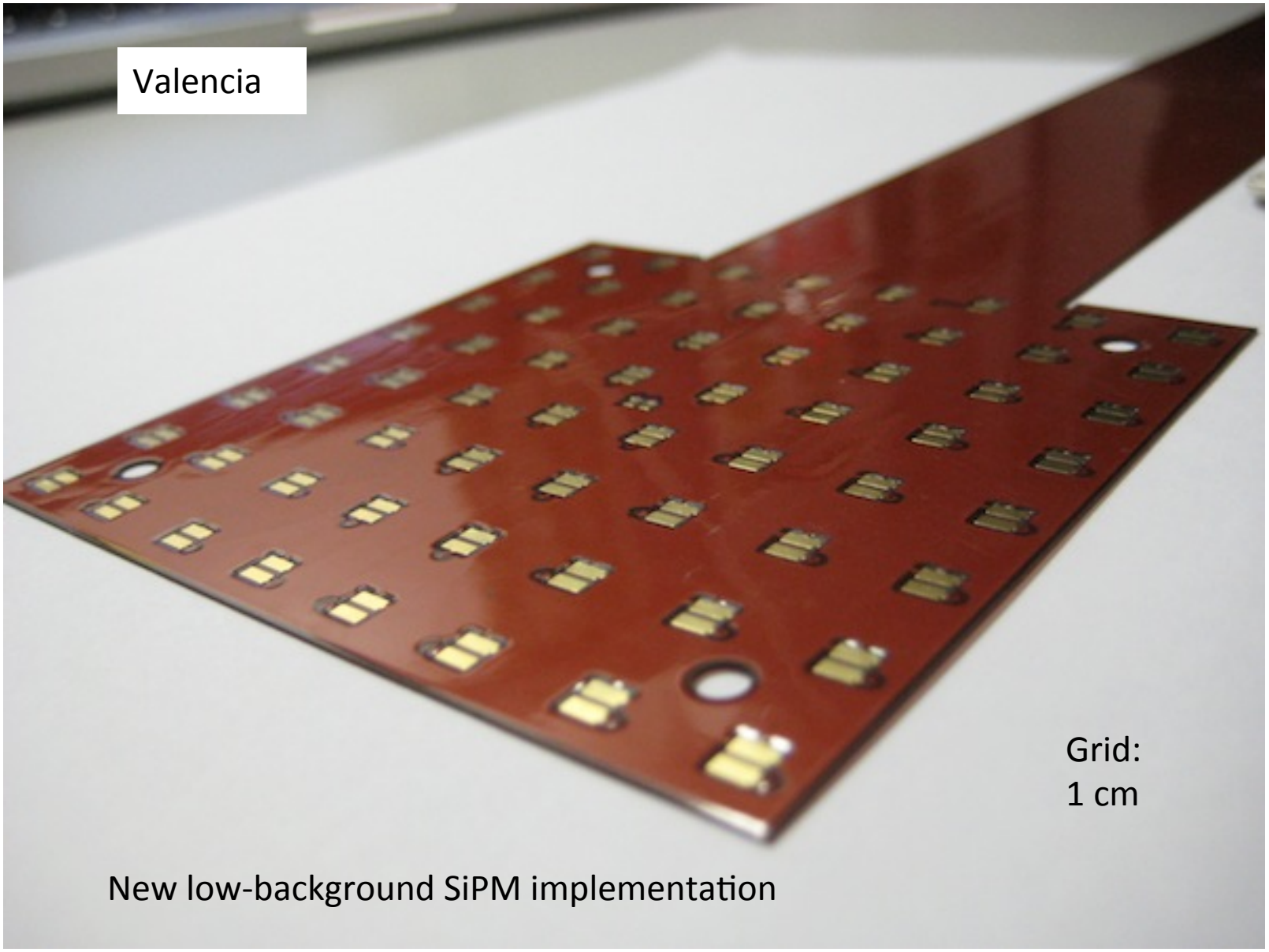
Topological signature - simulation



DATA: Real track from ^{137}Cs γ-ray – reconstructed with SiPMs



DATA from NEXT-DEMO IFIC, Valencia



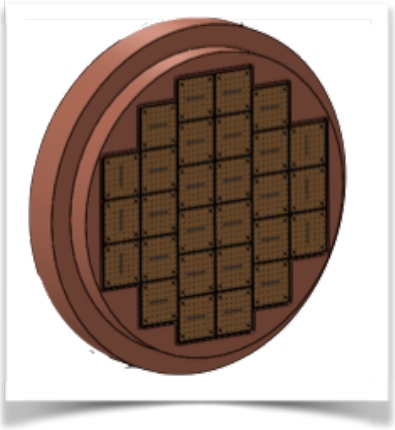
New low-background SiPM implementation

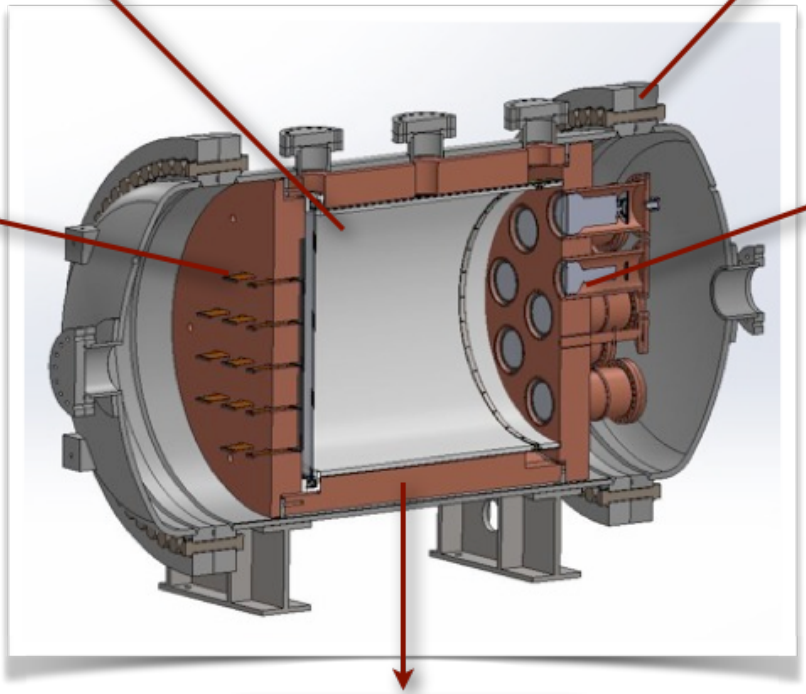
NEW (NEXT-WHITE) at glance

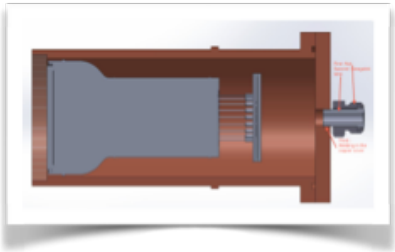
Time Projection Chamber:
10 kg active region, 50 cm drift length

Pressure vessel:
316-Ti steel, 30 bar max pressure

Tracking plane:
1,800 SiPMs,
1 cm pitch

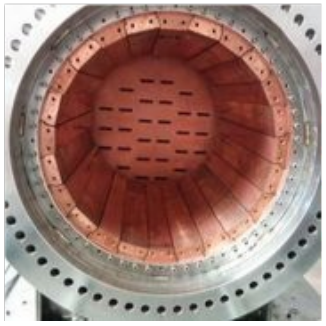






Inner shield:
copper, 6 cm thick

NEW being commissioned at LSC



Identify the barium daughter by optical spectroscopy

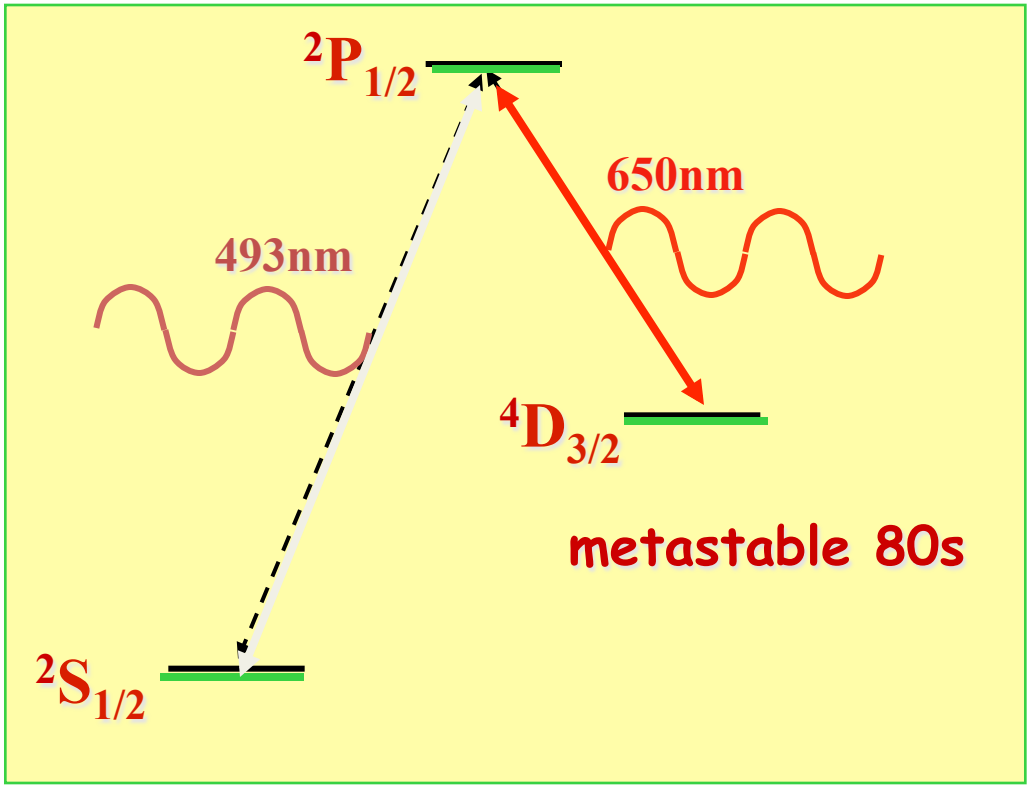
(M.Moe PRC44 (1991) 931)

Ba^+ system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)

Single ions can be detected from a photon rate of 10^7/s

Triplet state is quenched in dense gas

Can excite with blue, look only for red



Xenon's barium daughter

- In the decay, barium is strongly ionized by the nascent electrons emerging from the nucleus.
- Ba^{++} is the expected outcome, after partial neutralization occurs by electron capture from neutral xenon (ionization potential 12.14 eV).
- Process stops at Ba^{++} because the ionization potential of Ba^{++} is 10.04 eV; it can't take another electron from a xenon atom.
- For the Ba^{+} spectroscopy to work, another electron must come from somewhere.
- Ba^{+} must be transported to low-pressure trap

Might there be another way?

- Perhaps. The technique of **Single Molecule Fluorescent Imaging** may be adaptable here.
- My idea is to exploit a remarkable chemical effect: the transformation of non-fluorescent precursors into a robust fluorescent state by capture and chelation of doubly ionized alkaline earth elements such as Ca^{++}

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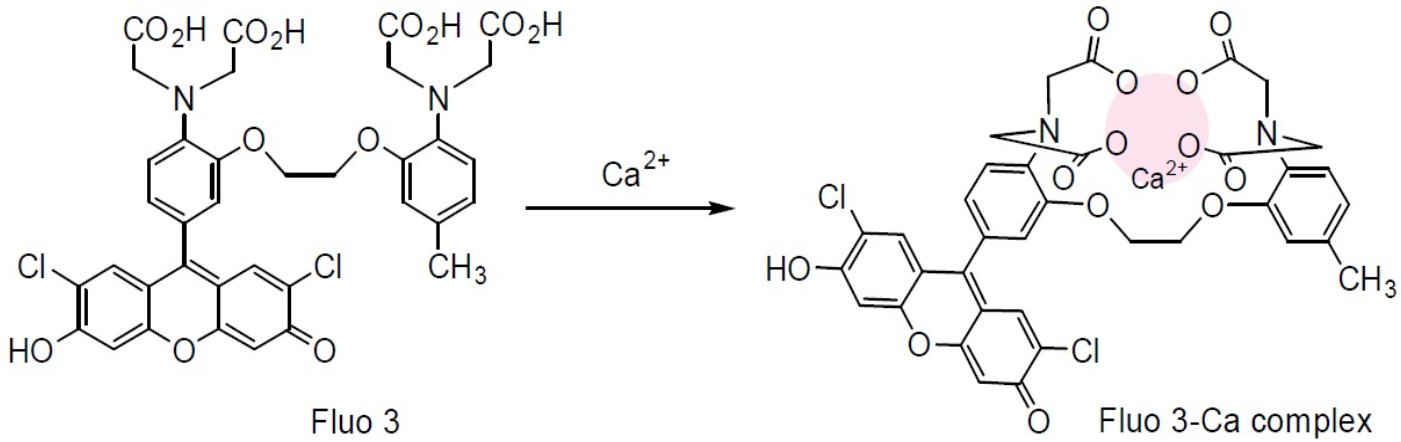
- Perhaps. The technique of **Single Molecule Fluorescent Imaging** may be adaptable here.
- My idea is to exploit a remarkable chemical effect: the transformation of non-fluorescent precursors into a robust fluorescent state by capture and chelation of doubly ionized alkaline earth elements such as Ca^{++}
- Maybe Ba^{++} too! Ca and Ba are congeners

Conformal changes in Fluo-3



Once Ca^{++} is captured by Fluo-3, its responsiveness to external excitation increases by a factor of 60 -80. Two-photon excitation with IR is also possible

This might work for Barium as well since barium and calcium are congeners. Fluorophores exist for for Pb^{++}, Hg^{++}, Cu…)

2014 Nobel Prize in Chemistry awarded to three physicists for developing SMFI

A TPC with a fluorescent cathode?

- One can imagine a cathode surface coated with untransformed fluorophores waiting to respond strongly after capture of one Ba^{++}.

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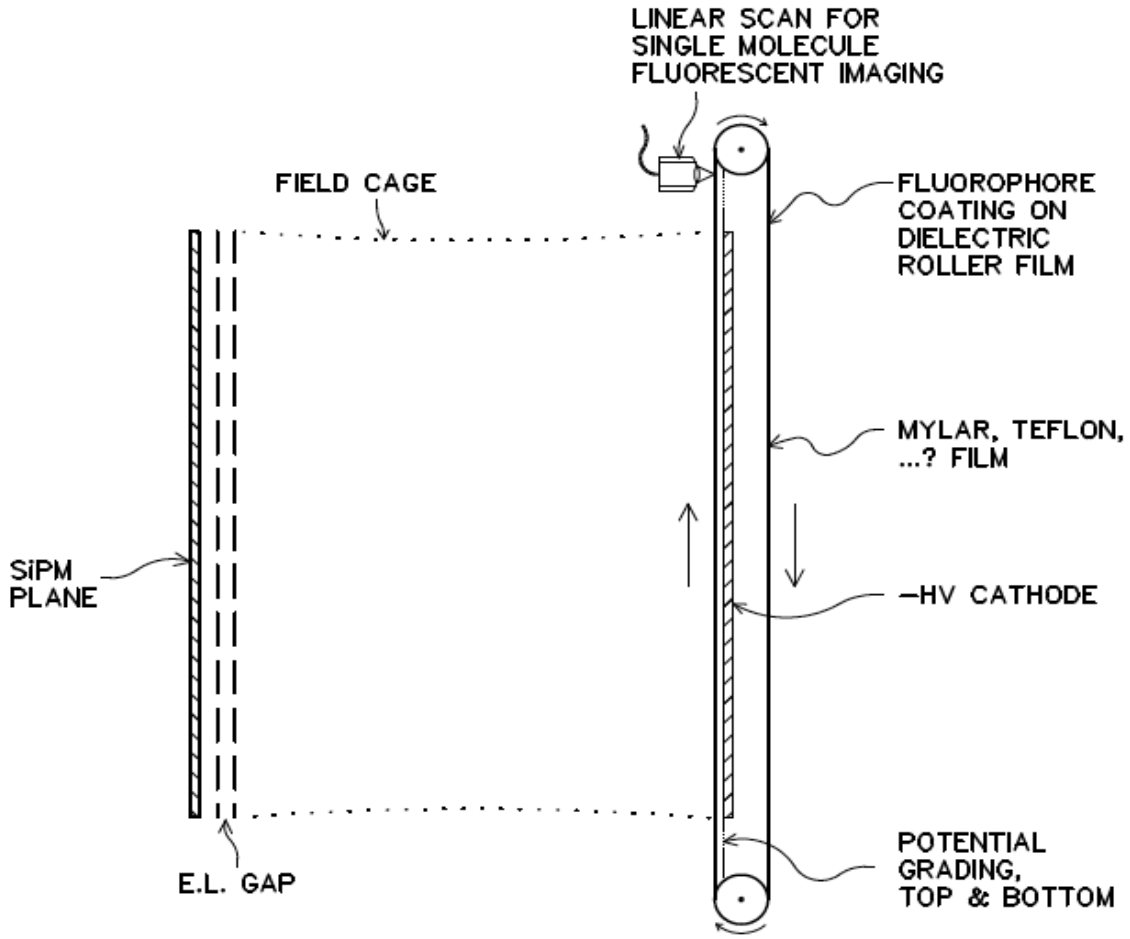
A TPC with a fluorescent cathode?

- One can imagine a cathode surface coated with untransformed fluorophores waiting to respond strongly after capture of one Ba^{++}.
- One can imagine that the cathode surface is a dielectric belt that transports at a few mm/s the latent image to a line imager.
- Ionization electrons liberated by the decay electrons provide a 3-D image of the event, and also the needed energy resolution, *a la* NEXT



HIGH PRESSURE XENON GAS ELECTROLUMINESCENT TPC
WITH SINGLE MOLECULE FLUORESCENT IMAGING OF BARIUM DAUGHTER

Summary & Perspective

- The need for a genuine **advance** is imperative.
- Is only a **background-free** experiment justifiable?
- **Gas-phase** Xenon offers flexibility and opportunities.
- **NEXT** is phased: 10 → 100 → ¿¿ 1000 ?? kg
- **NEXT** is somewhat behind more conventional techniques, but may hold **keys** to ultimate success.

Thank you

Backup slides

Energy resolution at $Q_{\beta\beta}$ = 2457 keV

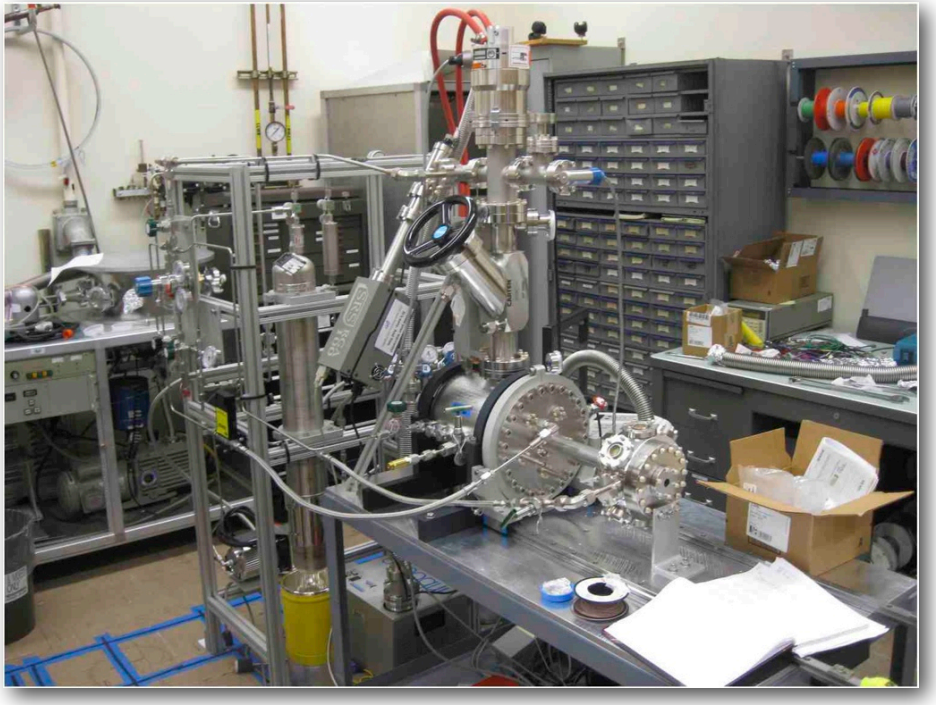
$$\delta E/E = 2.35 \cdot (F \cdot W/Q)^{1/2}$$

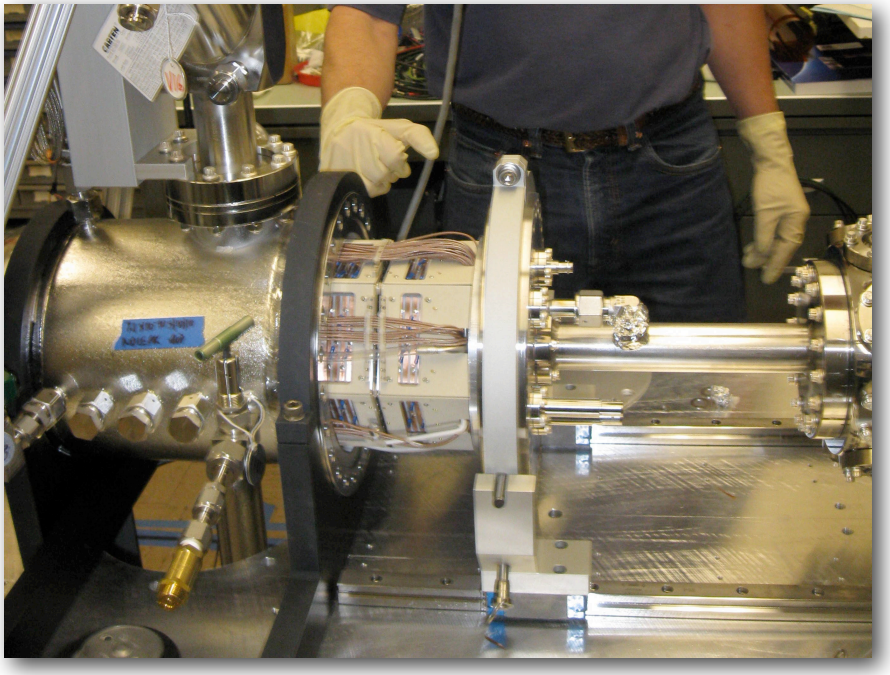
- F ≡ Fano factor (HPXe) : F = 0.15
- w ≡ Average energy per ion pair: w ~ 25 eV
- Q ≡ Energy deposited from ^{136}Xe --> ^{136}Ba:

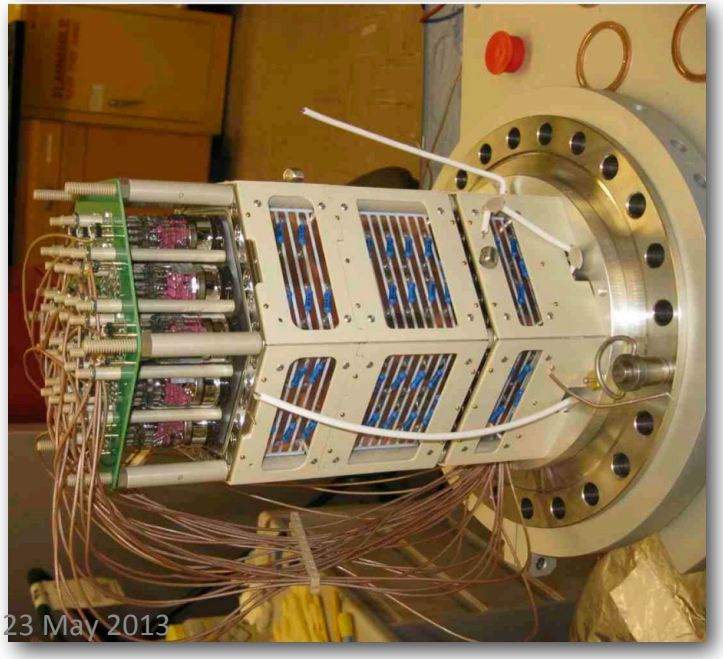
N = Q/w ~100,000 primary electrons

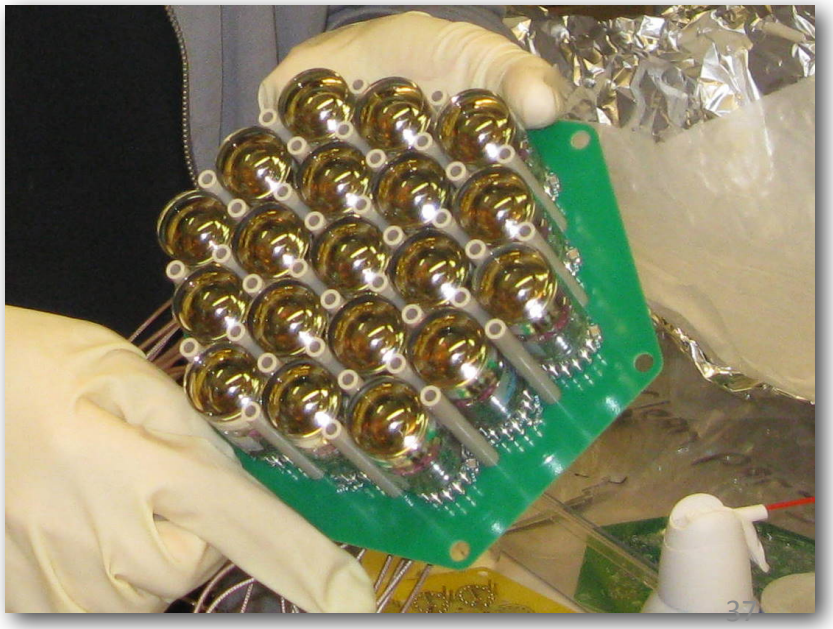
$\sigma_N = (F \cdot N)^{1/2}$ ~124 electrons rms!

$\delta E/E$ = 0.28% FWHM intrinsic HPXe









- $\beta\beta$ **decay: Rare transition between same A nuclei**
  - **Energetically allowed for some even-even nuclei**

- $(Z,A) \rightarrow (Z+2,A) + e^-_1 + \underline{\nu}_1 + e^-_2 + \underline{\nu}_2$
- $(Z,A) \rightarrow (Z+2,A) + e^-_1 + e^-_2$
- $(Z,A) \rightarrow (Z+2,A) + e^-_1 + e^-_2 + \chi$

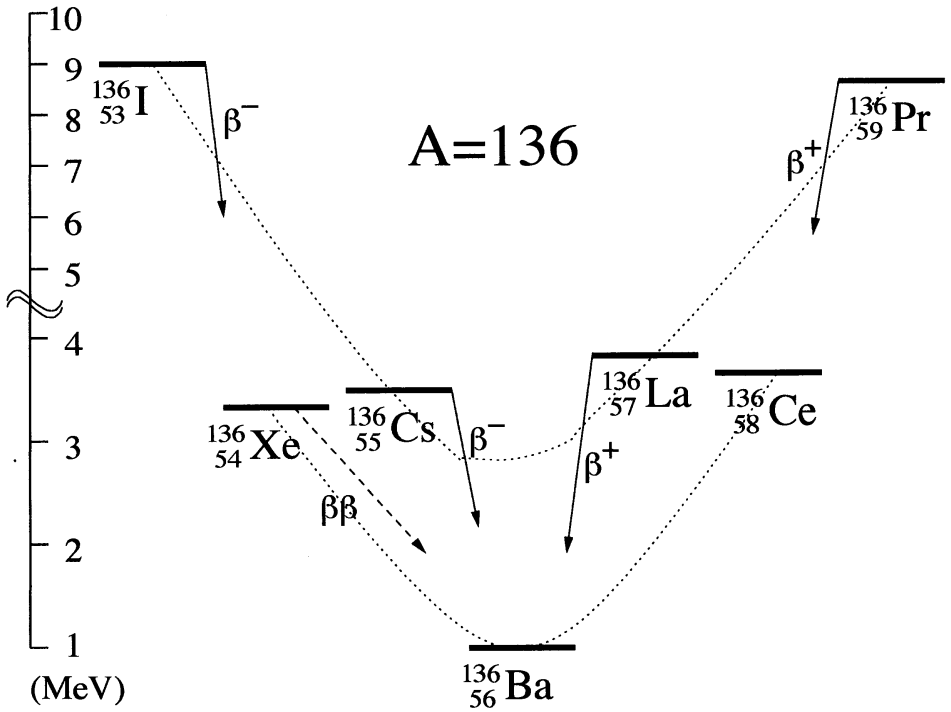


Figure 2.1: Simplified atomic mass scheme for nuclei with A=136. The parabolae connecting the odd-odd and even-even nuclei are shown. While ^{136}Xe is stable to ordinary beta decay, it can decay into ^{136}Ba by double-beta decay.

The neutrino effective mass m_ν

- Decay rate ≈ m_ν^2

$$\left[T_{1/2}^{0\nu}(0^+ \to 0^+)\right]^{-1} = G^{0\nu}(E_0, Z)\left|M_{\mathrm{GT}}^{0\nu} - \frac{g_V^2}{g_A^2} M_{\mathrm{F}}^{0\nu}\right|^2 \langle m_\nu \rangle^2$$

- Effective mass m_ν depends on phases:

$$\langle m_\nu \rangle^2 = \left|\sum_i^N U_{ei}^2 m_i\right|^2 = \left|\sum_i^N |U_{ei}|^2 e^{\alpha_i} m_i\right|^2$$

Experimental Parameters

$$\left\langle m_{\beta\beta} \right\rangle \leq \left(2.50x10^{-5}\, meV\right)\sqrt{\frac{W}{fx\varepsilon G_{0\nu}\left|M_{0\nu}\right|^2}}\left[\frac{b\Delta E}{MT}\right]^{\frac{1}{4}}$$

- W – molecular weight of source
- f – isotopic abundance
- x – number of bb isotopes per molecule
- ε – detector efficiency
- $G_{0\nu}$ – decay phase space
- $|M_{0\nu}|$ - matrix element
- b – background in counts/keV-kg-y
- ΔE – energy window in keV
- M – mass of source in kg
- T – counting time in years

- When comparing isotopes, don't forget W, favors low A. $G_{0\nu}$ favors high A.
- QRPA has more A dependence than SM.

Isotope	$\sqrt{(W/(G_{0\nu}\|M_{0\nu}\|^2))}$ x10^7
Ge	2.4(QRPA) 4.7(SM)
TeO_2	1.9(QRPA) 3.1(SM)
Xe	2.4(QRPA) 3.3(SM)

The Experimental Challenges

Maximize Rate/Minimize Background

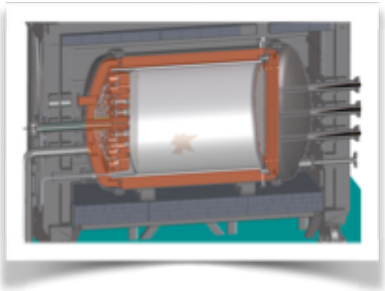
$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\Delta E}{M t_{live}} \right)^{\frac{1}{4}}$$

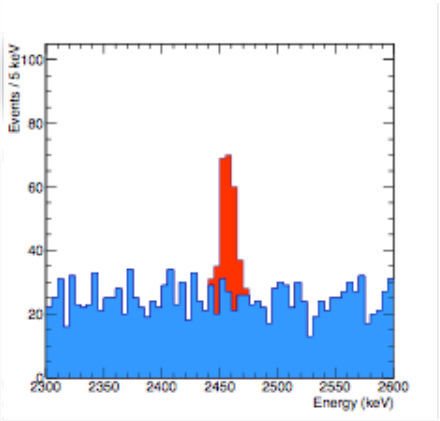
b = background/keV
ΔE = Energy ROI
M = active isotopic mass
t_{live} = graduate students

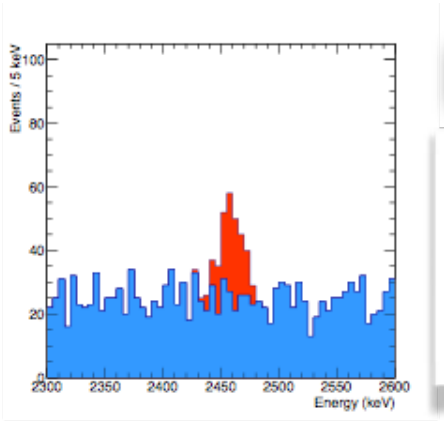
Large Mass (~ 1 ton)
Large Q value, fast $\beta\beta(0\nu)$
Good source radiopurity
Demonstrated technology
Ease of operation
High isotopic abundance
Easy enrichment
Small volume, source = detector
Good energy resolution
Slow $\beta\beta(2\nu)$ rate
Identify daughter in real time
Event reconstruction
Nuclear theory

Energy resolution

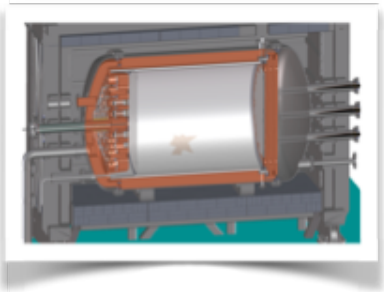
0,5 % FWHM



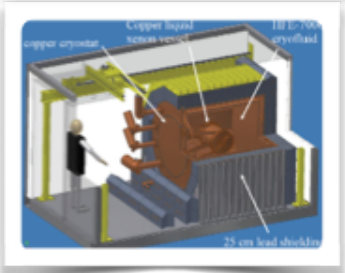


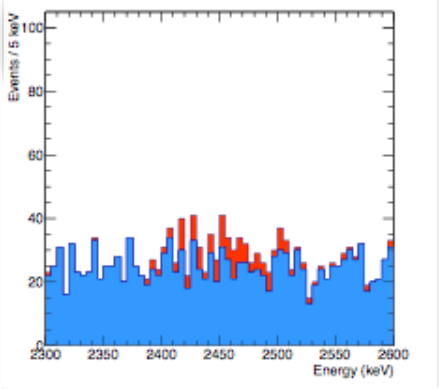


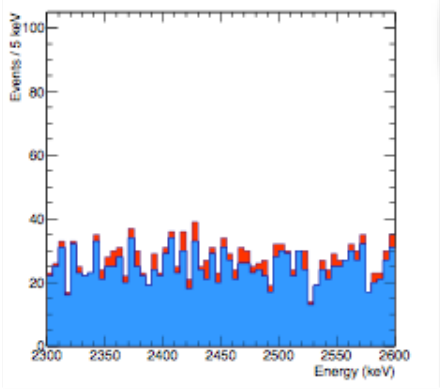
1,0 % FWHM



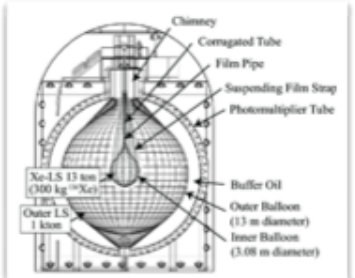
4,0 % FWHM







10 % FWHM



Signal and background:

- Signal: mv ~200 meV and an exposure of 5 ton year.
- Background 1 count/keV/ton/year.

Energy scale for Xe

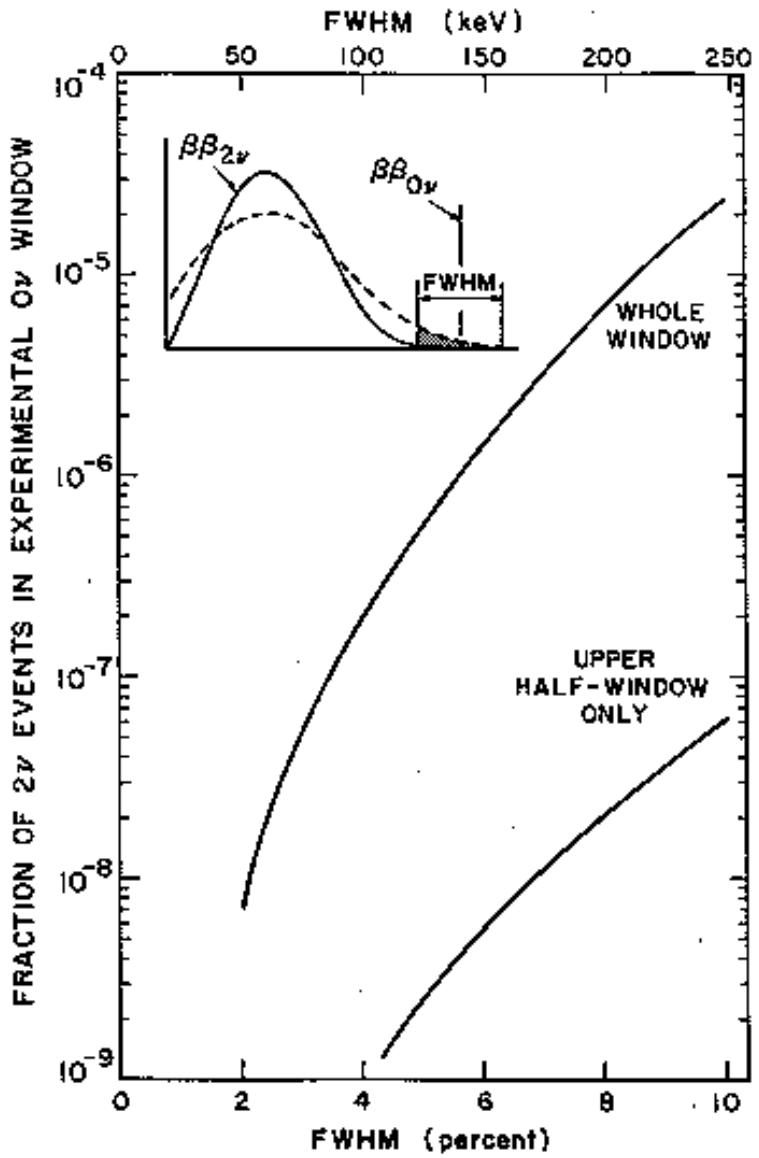
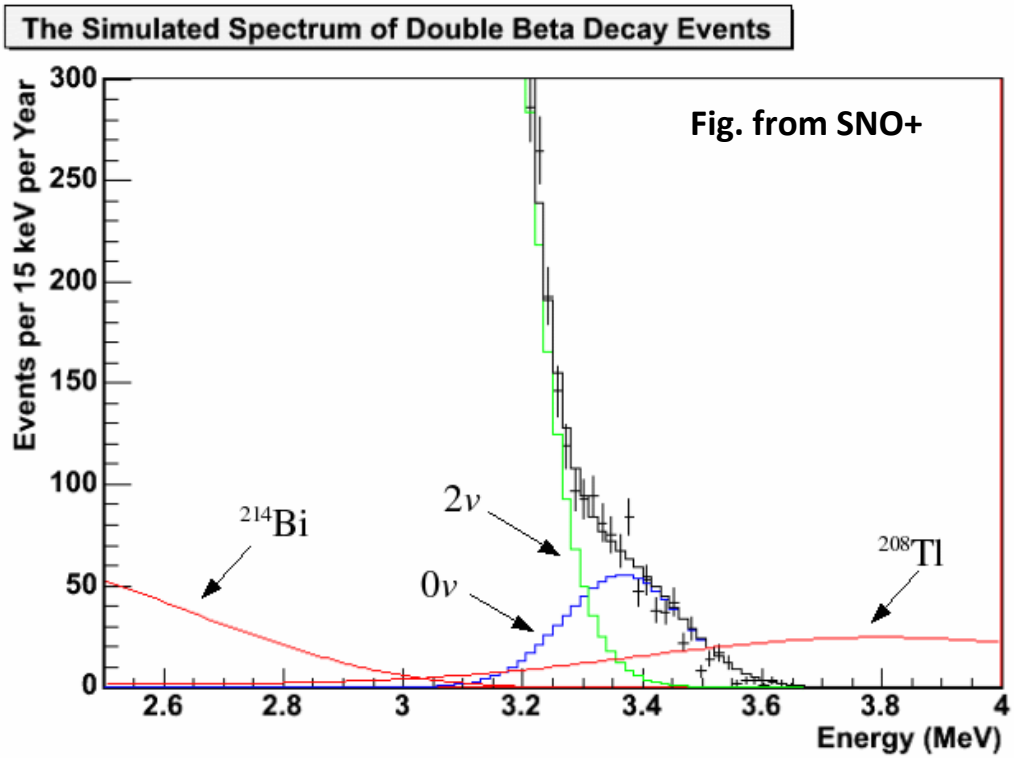


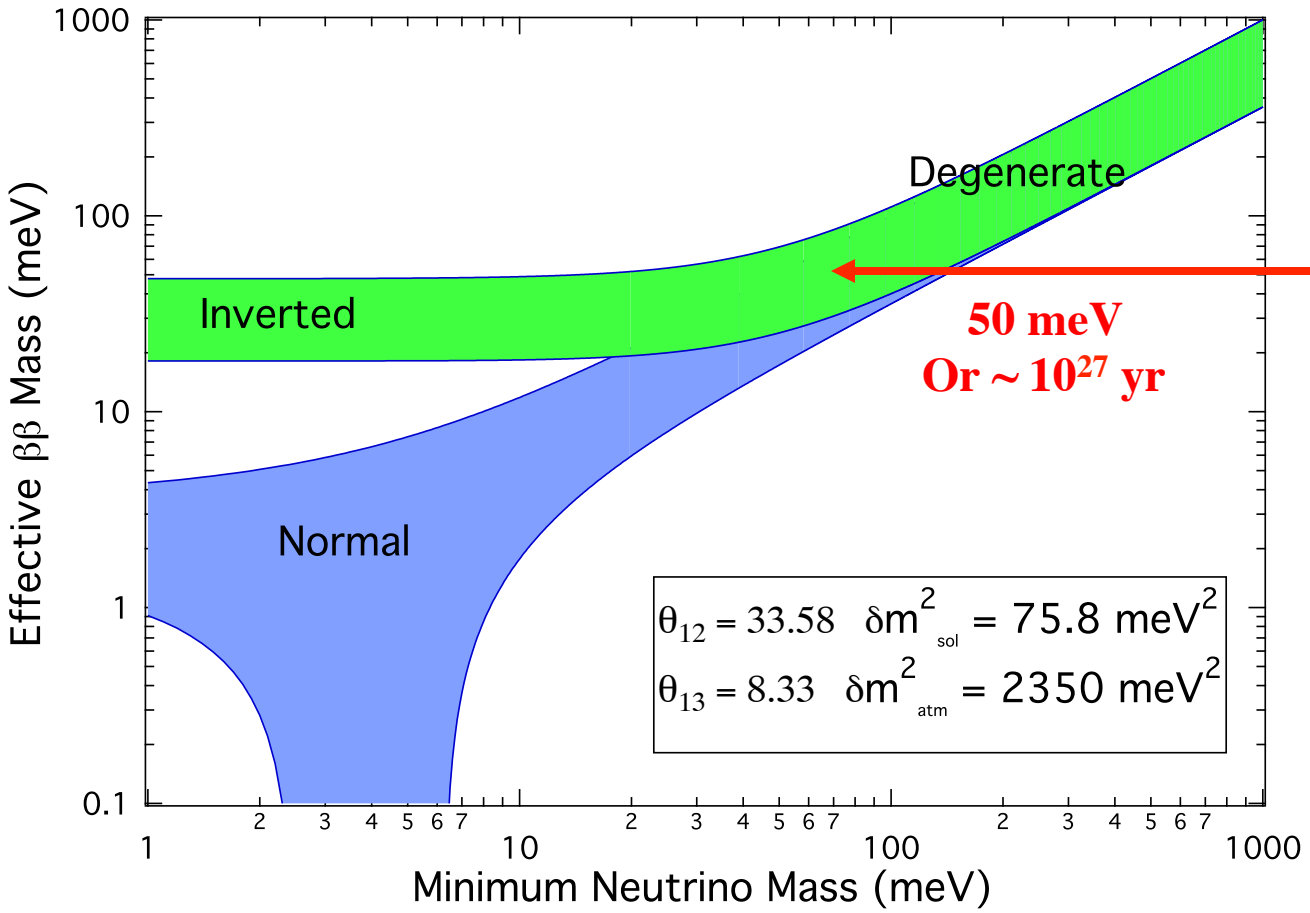
Figure from Mike Moe

Splitting the window, or in the case of high-event rates, fitting the spectrum.



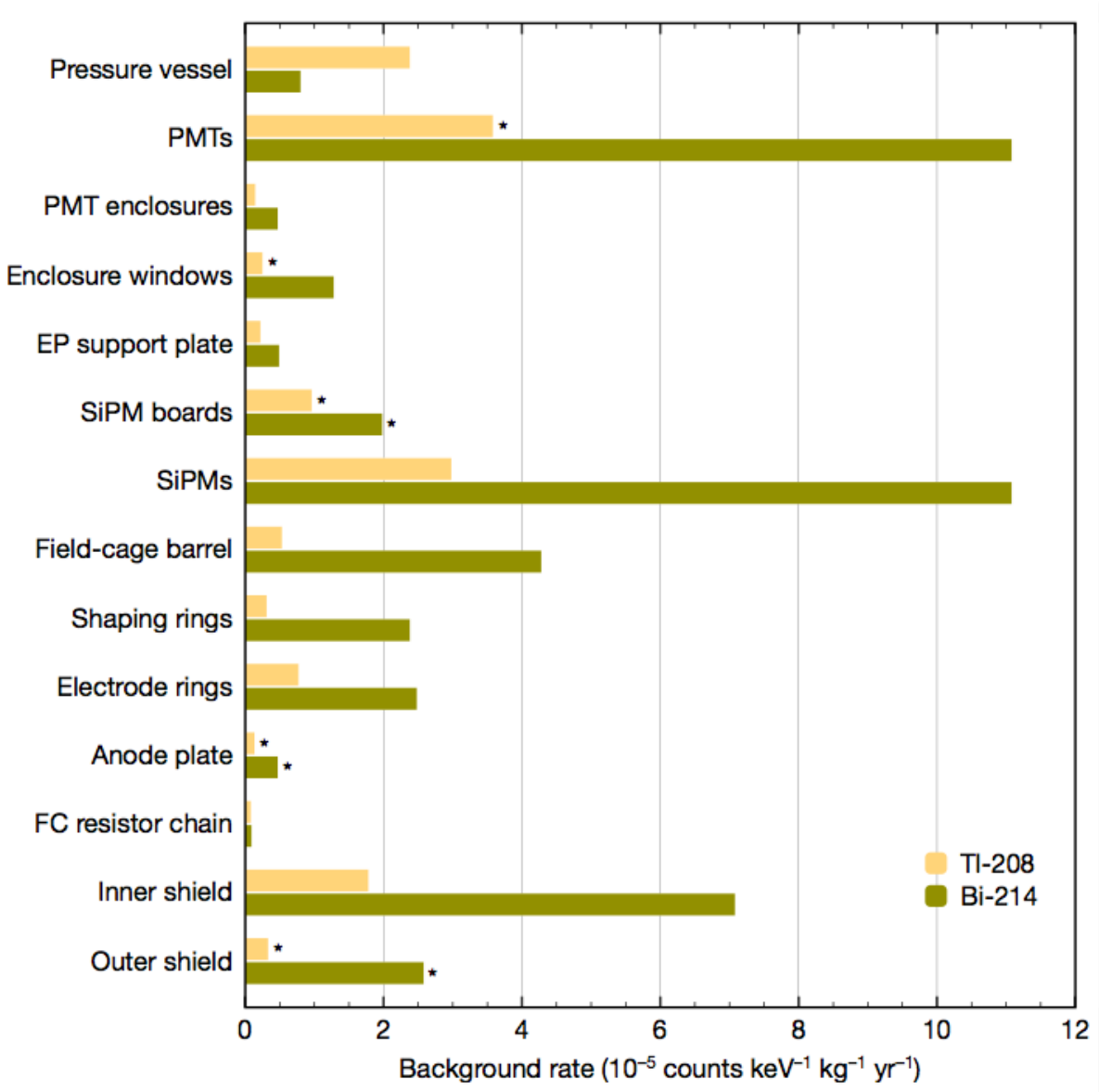
ββ Sensitivity

(mixing parameters from arXiv:1106.6028)



Even a null result will constrain the mass spectrum possibilities!

A $m_{\beta\beta}$ limit of ~20 meV would exclude Majorana neutrinos in an inverted hierarchy.



Background model dominated by limits rather than by actual values